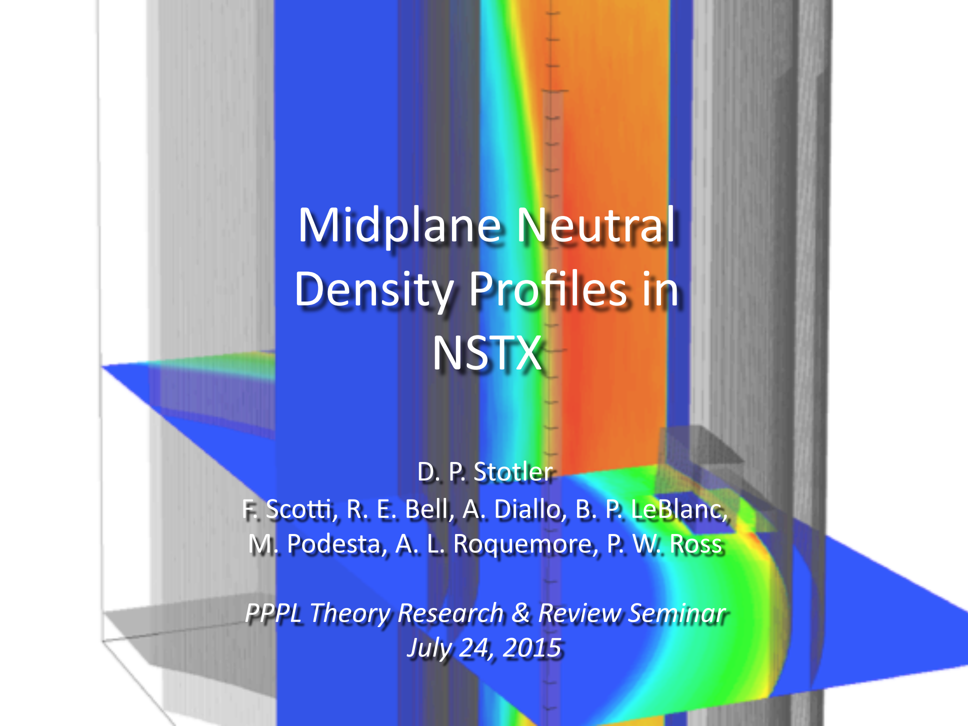

Midplane Neutral Density Profiles in NSTX

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PPPL Theory Research & Review Seminar
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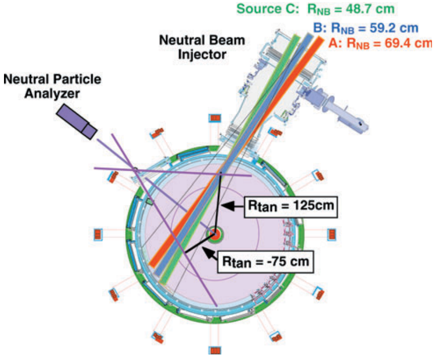
Preview

- Describe a simulation based method for inferring midplane neutral density profiles from visible camera data.
- Get a range of values for 2010 NSTX discharges: $n_{\mathrm{D}} \sim 10^{16}$ m^{-3}, $n_{\mathrm{D}_2} \sim 10^{17}$ m^{-3}.
- Validation quantifies uncertainties in simulation results $\Rightarrow$ error bars and pointers for improving model & experiment.
- If you leave / fall asleep:
  - D. P. Stotler et al., *J. Nucl. Mater* **463**, 897 (2015).
  - D. P. Stotler et al., *Phys. Plasmas* (August 2015), PPPL-5093.

Multiple Needs for Main Chamber Neutral Density Profiles

- For other diagnostics & analyses
  - Neutral beam charge exchange loss power,
  - Interpretation of CHERS data.
- & for study of SOL & pedestal physics,
  - H-mode pedestal formation,
  - Edge plasma turbulence.



[S. Medley, NF (2004)]

Direct Experimental Inversion of Limited Utility

- Visible camera $\Rightarrow$ line integrated emission rates.
- Abel inversion $\Rightarrow$ volumetric rate S.
- Balmer-β emission rate:

$$S_\beta = n_\mathrm{D}(1s)\left[\frac{n_\mathrm{D}(n=4)}{n_\mathrm{D}(1s)}\right] A_{4\rightarrow 2} \equiv n_\mathrm{D} F(n_e, T_e),$$

$$\Rightarrow n_\mathrm{D} = S_\beta / F(n_e, T_e).$$

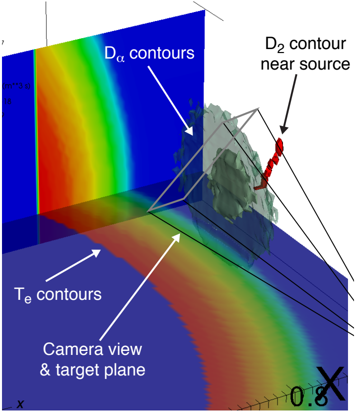
- But, S_β & F both significant only in narrow radial region,
- DEGAS 2 based "forward" method for inferring $n_D(R)$, $n_{D_2}(R)$ provides more information, smaller uncertainties.

DEGAS 2 Monte Carlo Neutral Transport Code

- Simulate behavior of neutral species in a plasma.
  - Plasma-wall interactions generating neutral atoms & molecules, e.g., recycling.
  - Interactions between those neutral species with plasma ions & electrons as they penetrate.
- Input to DEGAS 2:
  - Geometry: 2-D or 3-D outline of hardware & flux surface aligned mesh for plasma.
  - Plasma density, temperature, flow velocity everywhere.
  - Source of neutrals: recycling, gas puff, recombination, ...
- $\Rightarrow$ Volumetric sources / sinks of plasma mass, momentum, & energy due to those interactions (e.g., for coupling to plasma codes).
- & Synthetic diagnostic data for experimental comparison,
  - Neutral pressure,
  - Light emission,
  - Wall fluxes.

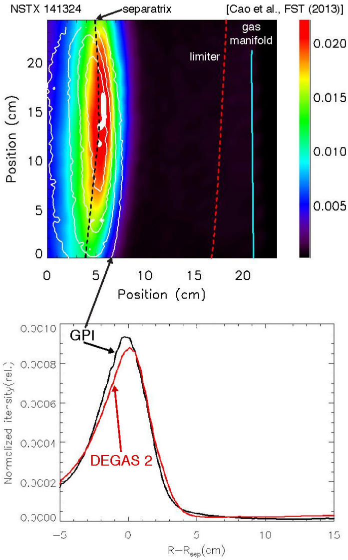
Method Leverages Off Successful Midplane Gas Puff Imaging Simulations

- See: [B. Cao et al., Fusion Sci. Tech. **64**, 29 (2013)].
- Relies on nearby $n_e(R)$ & $T_e(R)$ from Thomson scattering,
  - & assuming $n_e(R)$ & $T_e(R)$ constant on flux surface ⇒ know everywhere.
- Flux surface shapes from EFIT,
  - Thomson profiles mapped via R ⇒ not sensitive to separatrix location.



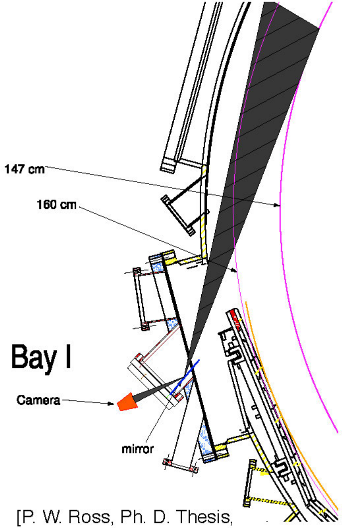
Validated DEGAS 2's Description of D_2 Penetration from Far SOL

- D_α radial profiles from D_2 puff matched within estimated uncertainties.
- & matches absolute magnitude,
  - Camera absolutely calibrated,
  - Know total amount of gas injected $\Rightarrow$ compare photons recorded / D injected.
  - GPI: $1/89 \pm 34\%$,
  - DEGAS 2: $1/75 \pm 18\%$.
- $\Rightarrow$ DEGAS 2 provides adequate model for D_2 penetration of NSTX midplane.



Key Data: Passive Light Emission from Edge Neutral Density Diagnostic (ENDD)

- Absolutely calibrated tangential camera,
  - $\Rightarrow$ Radial profile, 1.6 mm resolution.
- 3.7 ms exposure time $=$ 268 frames / second.
  - $\Rightarrow$ integrates over ELMs.
- 20 cm radial $\times$ 9 cm poloidal.
- Has D_β filter for shots considered here.
- Complete spatial calibration $\Rightarrow$ can build DEGAS 2 synthetic diagnostic.



[P. W. Ross, Ph. D. Thesis, Princeton University (2010)]

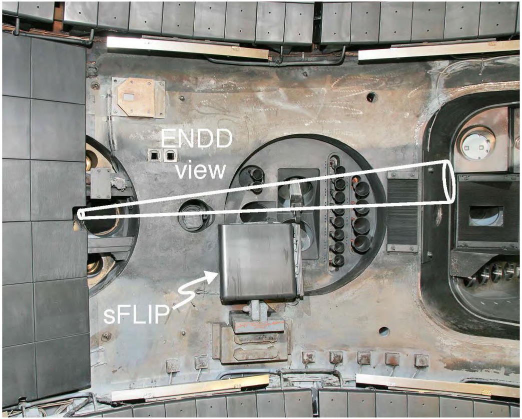
Set Up DEGAS 2 Simulations Similar to Those Used for GPI

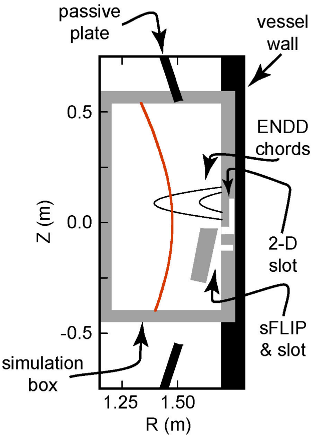
- Geometry & plasma setup procedures derived from those used for GPI [B. Cao et al., Fusion Sci. Tech. **64**, 29 (2013)],
- Geometry based on EFIT flux surface contours,
- Plasma profiles from Thomson & CHERS,
  - Use CHERS to estimate n_{D^+}/n_e & T_i/T_e,
  - $T_i = T_e$ for shots used here.
- Primary differences from GPI:
  - Nature of D_2 source,
  - Synthetic diagnostic for D_β ENDD,
  - Baseline runs ignore D_β from molecules.

Source Characterization & Analysis Procedure Specific to ENDD

- Actual sources difficult to characterize:
  - Neutral flow from divertor,
  - Main chamber recycling,
  - Or outgassing.
- $\Rightarrow$ Postulate vertically uniform D_2 source coming from vessel walls,
  - Will show results very insensitive to this assumption.
  - Assign arbitrary magnitude: $\Gamma_{D_2} = 10^{20}$ $D_2/(m^2$ s) at wall.
- Compare synthetic ENDD signal with experimental image:
  - Use horizontal row of simulated ENDD pixels at $Z = 9$ cm,
  - Overlay with row from calibrated experimental ENDD smoothed over vertical 10 pixels (1.4 cm)
    $\Rightarrow$ overall scale factor for simulation.
- Focus here on 2-D / axisymmetric calculations.

ENDD Geometry

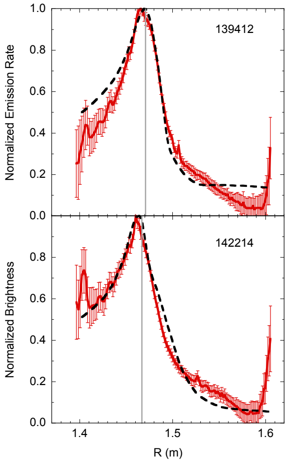




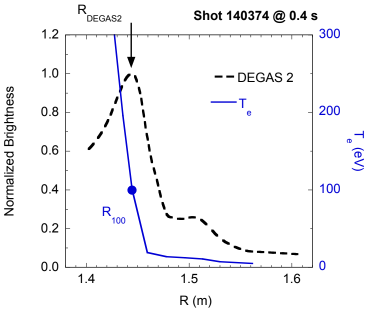
- Scintillator Fast Lost Ion Probe [sFLIP, Darrow, RSI (2008)]: used for initial 3-D runs. But, not here.

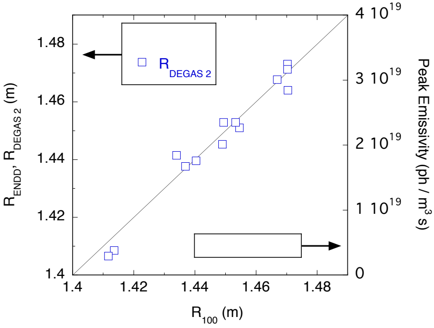
Emission Profiles Agree Reasonably

- Apply to two NSTX H-mode plasmas:
  - 139412 $t = 4$ s: $\delta = 0.3$, ELMy,
    - Lull at $t = 0.4$ s.
  - 142214 $t = 4$ s: $\delta = 0.6$, ELM-free.
- High SOL density, $n_e \sim 10^{18}$ m^{-3} $\Rightarrow$ Thomson accurate at all points.
- Take ratios of profile peaks:
  - 139412: ENDD = 2.5 $\times$ DEGAS 2,
  - 142214: ENDD = 1.6 $\times$ DEGAS 2.
- Good match confirms approach to inverting ENDD & adequacy of uniform D_2 source ansatz.
- But, what is "good"?
  $\Rightarrow$ that's the point of validation!



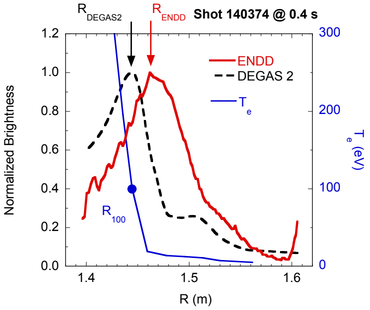
Simulated Peak Location Tracks $T_e = 100$ eV

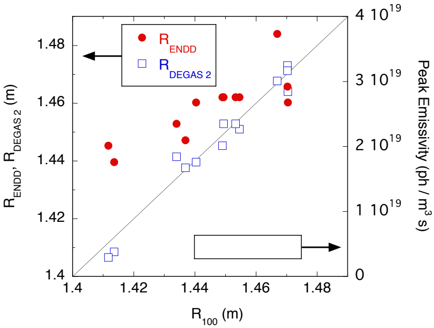




- 12 runs from 7 shots.

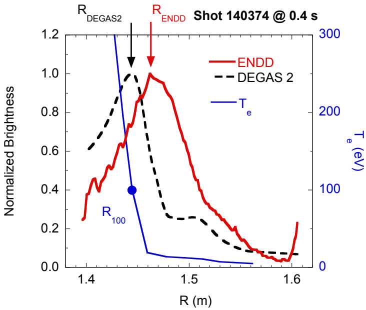
$R_{\text{ENDD}} - R_{\text{DEGAS2}}$ Ranges from $-1 \to 4$ cm

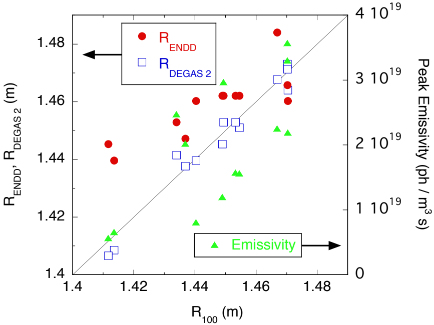




- Discrepancy larger for smaller R_{100}!

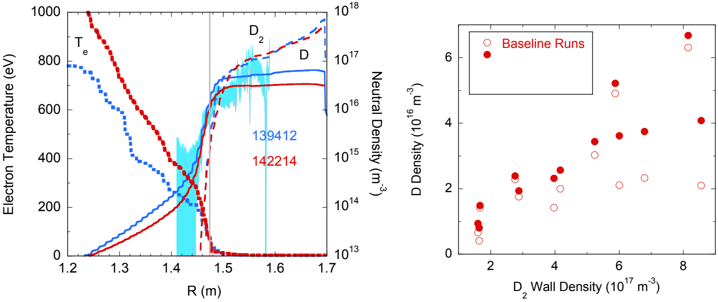
Emissivities Also Correlated with R_{100}





- Physics? Diagnostic problem? Simulation problem?

Each Simulations Yields Neutral Density Profiles at Midplane



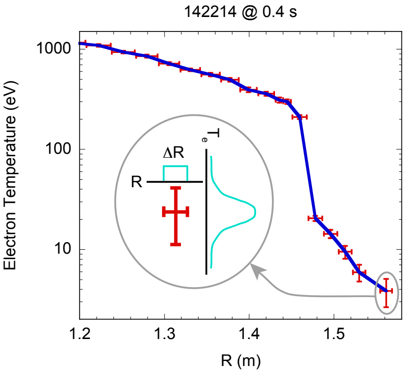
- $\Rightarrow$ Ranges of values at vessel wall, $R = 1.7$ m. Key result!
- But, how uncertain are they???

Estimated Uncertainties from ENDD Itself Are Small

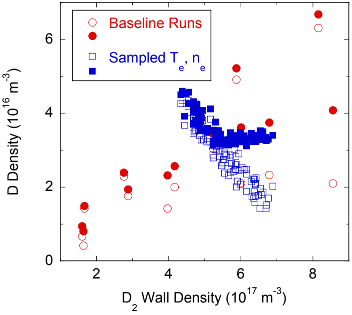
- Absolute calibration of camera: 3%.
- Spatial calibration of camera: 3 mm
- "Blue shifting": 8% magnitude,
  - Negligible effect on peak location.
- Li coatings on mirror?
  - Expect insignificant & not evaluated.

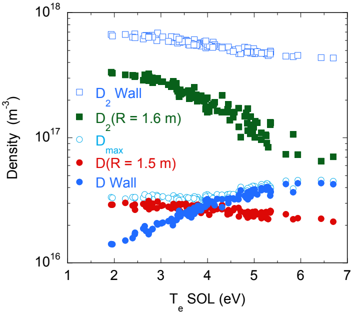
Peak Location Tracks Plasma Profiles ⇒ Assess Associated Uncertainties

- Thomson scattering profiles uncertain due to random & systematic errors, as well as finite sampling volume.
- Do Monte Carlo sampling of these errors ⇒ 100 T_e, n_e profiles for 142214.
- ⇒ 100 runs ⇒ distribution of peak locations, neutral densities.



Yields Distributions of Output Quantities

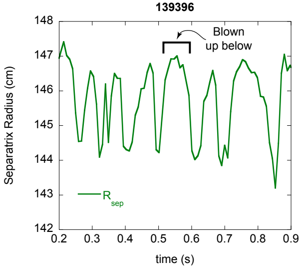


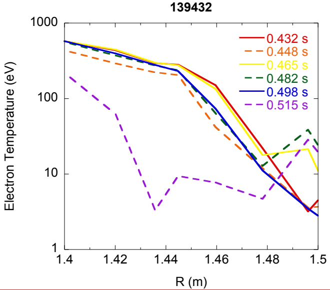


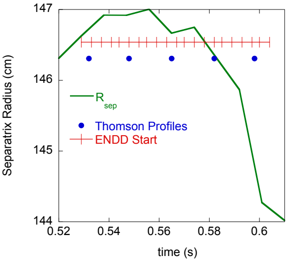
- Peak location standard deviation: 3 mm.
- Density standard deviations: n_{D_2}: 6.6×10^{16} m^{-3}, n_D: 7.5×10^{15} m^{-3}.
- Also, quantify sensitivity of densities to SOL T_e

Plasma & Separatrix Motion ⇒ 1 cm Uncertainty in Peak Location

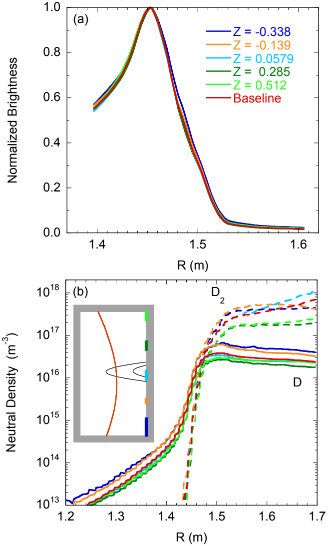
- Motion of plasma significant during 4 ms exposure
  ⇒ ENDD is an average.
- But, ∼ 4 frames between TS pulses. How to match up?
- 1 cm estimate from motion in 139396, 139432 & others.







Quantify Uncertainties Associated with Source Profile Assumption

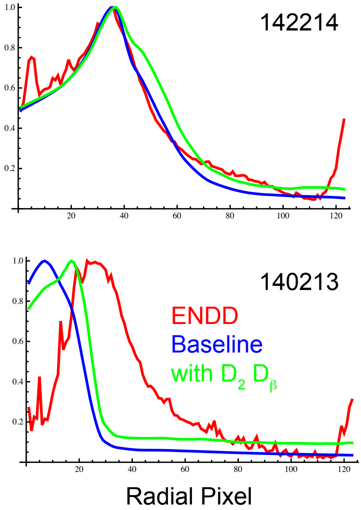


- Relative deviations from baseline ENDD are $\leq$ 18%,
- Density profiles differ by factor of 2 - 3 or less.
- Similar conclusions from runs with sources at bottom boundary.

Molecular Contributions May Be Important

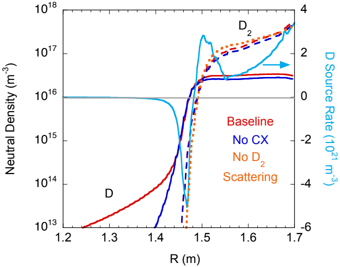
$$e + D_2 \rightarrow e + D(1s) + D^*(n = 4),$$
$$e + D_2^+ \rightarrow e + D^+ + D^*(n = 4),$$
$$e + D_2^+ \rightarrow D(1s) + D^*(n = 4).$$

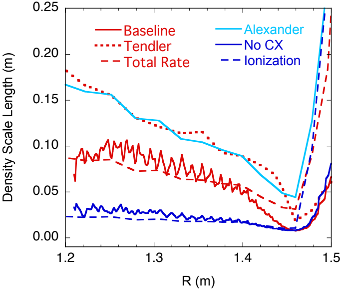
- In GPI: D_2 $D_\alpha \sim 40\%$ of emission at peak. Here?
- Problem: D_β rates not as well tested as D_α
  $\Rightarrow$ only an estimate.
- Contributes $35 \rightarrow 50\%$ of total emission!
- Active at lower T_e than D emission
  $\Rightarrow$ can shift emission peak!



Effect of Charge Exchange Surprisingly Small!

- Remove CX from reaction list: $<$ 19% difference in ENDD profile,
  - D, D_2 densities at wall drop 17, 13%.
- Even though $\langle \sigma v \rangle_{\mathrm{CX}} > \langle \sigma v \rangle_{\mathrm{ion}}$ over most of volume.
- Dominant process is instead D creation from D_2.
- CX *is* relevant for $R < R_{\mathrm{DEGAS2}}$.



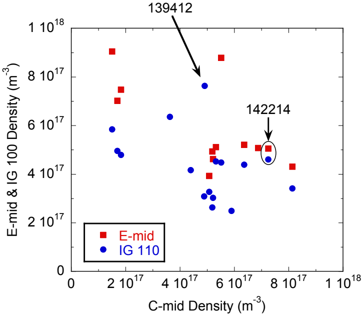


Summary

- Described method for inferring density profiles.
- Simulated ENDD profile peaks differ from measured by $\leq$ 4 cm,
  - Uncertainty due to plasma motion: 1 cm,
  - From preliminary D_2 D_β emission model: $\leq$ 2 cm.
- Factors preventing more complete resolution:
  - Plasma parameters in SOL,
  - Plasma motion & synchronization,
  - D_2 D_β model,
  - Unaccounted for camera calibration issues.
- Nonetheless, deviations small compared with problem scale $\Rightarrow$ can use results to get approximate densities.
- $\Rightarrow n_{\mathrm{D}} = 1$ to 7×10^{16}, $n_{\mathrm{D}_2} = 2$ to 9×10^{17}.

Can We Compare Vessel Densities with Micro-Ion Gauge Data?

- Survey C-mid, E-mid, IG 110 pressures in 17 shots,
  - Averaged over 0.1 or 0.2 s interval,
  - IG 110 shifted 0.18 s.



- No obvious correlation between them!
- Each is compromised:
  - C-mid very noisy (low end of operating range?),
  - E-mid direct view of plasma $\Rightarrow$ affected by ELMs,
  - IG 110 slow to respond.
- Can only get an upper bound or range of vessel densities.
- Similarly, see no correlations with peak ENDD emissivity.